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Joining Feasibility Between Metallic- and Polymeric-Based Materials by Friction Stir Forming

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Abstract

Nowadays, the research efforts must result in a reduction of environmental pollution emissions. Consequently, the products have to be designed in such a way that the performance criteria are achieved at the minimum weight. Taking the lightweighting to its extreme and aiming at satisfying the product requirements, a revolutionary body concept should result in an optimal material selection and distribution. The joining methods, among many manufacturing technologies, have been considered as key enabling solutions in making innovative and sustainable products. The joint between dissimilar materials is a current challenge and different solutions have been proposed in each of the joining categories, i.e. adhesive bonding, welding and mechanical fastening. In the proposed research, the fastenerless-riveting by friction stir extrusion has been analyzed to connect metallic- and polymeric-based materials in a single shot process sequence. Specifically, the process consists of a rotating non-consumable tool, which is first vertically dipped inside the metal sheet (according to a specific penetration depth p), and after a heating up idle time, the tool moves (according to a rotational speed (S) and to a forming velocity (v)) through the sheet, stirring and extruding the material into a further blank, placed below the metal one and previously holed. The analyzed materials, an aluminum alloy (AA1050) and a high-performance plastic (PEEK), were chosen because they are characterized by extremely different thermal properties, starting from their working and melting temperatures. In this regard, friction stir forming leads to a temperature variation around the working area, which could result in a not joining phase feasibility owing to the material dissimilarities. Herein, AA1050 and PEEK parts were connected by extruding the pins from the metal sheet. Different process configurations were investigated to test the joint feasibility in a one-shot sequence and the results discussed.

Keywords: Joining; Mechanical Fastening; Friction Stir Process; Composite; Dissimilar Materials

1. Introduction

The need to combine different materials is common to many industrial sectors as the integration of multiple parts improves design flexibility and allows an optimal combination of different properties. Nowadays, hybrid components, i.e. elements obtained combining dissimilar parts, are widely employed in various industrial applications pursuing weight and/or cost reduction as well as performance improvement [1]. Examples of hybrid structures have resulted in combination of materials with very different properties, such as metals and advanced composite materials that imply manufacturing process and/or operating life difficulties owing to thermal or chemical incompatibilities of the materials that are combined [2]. Anyway, applications of these multiple-parts solutions have been meeting consistent interest in specific sectors, such as the transportation industries, where mass reduction, without renouncing to safety of the vehicle body, is fundamental to obtain reduction in CO_2 emissions. Indeed, the strategies of product making must be focused on how they affect the environment [3]. The material selection in component design contributes to the environmental impact of the component service-lives and, therefore, the feasibility of alternative manufacturing solutions needs to be evaluated in making new

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parts. In this context, different joining processes can be employed in building hybrid components [4]. These processes are divided into three macro groups: mechanical fastening, adhesive bonding and welding technique. In addition, these processes can be used individually or combined in a single solution ensuring a successful joint. Specifically, mechanical fastening includes several solutions, which usually require additional clamping equipment and performs the connection without melting the joint surfaces. Initially, bolted joints [5] were widely used to connect metal-metal materials, but, currently, this joining technique has been always more utilized for polymer-polymer combinations and also for constructing metal-polymer structures. In any case, this process solution remains the most used method for joining different components, thanks to the simplicity of the process and to the performance of the connection nevertheless some limitations must be considered, such as the increase in the part weight and the evolution of the stresses around the connection areas, which could induce degradation and corrosion problems.

The weight increment can be avoided by clinching the parts [6]. Indeed, this is a mechanical fastening solution, widely used for the manufacture of body panels in the automotive industry, which exploits the plastic deformation of the material to be joined to form a mechanical interlock. Furthermore, clinching has been a popular alternative for joining different materials implying, however, an initial warming up phase and a consistent decrement of the connection properties.

Adhesive bonding [7], instead, is based on the formation of intermolecular forces between the materials and the polymeric adhesive, necessary for the formation of the joint, allowing significant weight reduction and a homogeneous distribution of the load stresses compared to bolted joints. However, adhesive joints can be problematic, since they cannot be dismantled without damage. Another important factor limiting the use of the adhesives is the uncertainty in predicting their long-term durability, especially when the parts are subjected to environmental factors, such as temperature and humidity. It is worth to consider that glued joints often fail instantly, rather than progressively, when applied in engineering structures. Finally, adhesive connections usually require surface pretreatment and longtime curing of the employed resins, which affect the process productivity.

Finally, welding techniques [8], usually performed by melting the base or filler materials in the connection areas are not ideal for joining hybrid parts, especially if they have different thermal properties that, in the most critic combination, can result in a degradation of the material characterized by the lower melting temperature. Nevertheless, promising techniques have been developed in order to overcome the problems related to welding dissimilar materials. Ultrasonic [9] and laser welding [10] are two solutions, which have been developed offering the possibility to heat the surfaces to be joined, locally, creating solid state conditions fundamental if materials with different thermal properties are processed.

Friction stir techniques [11] have also to be included in this solid-state welding line. The most known variant is probably the friction stir welding, which, first plunging and subsequently moving in parallel to the surface to be joined, a specific rigid tool creates the stringer bead without melting the material, but just by its severe plastic deformation. Friction spot welding, friction lap joining and friction spot joining are other solutions which exploit the material heating due to friction for producing the working conditions suitable for the part connection.

In this work, the attention has been focused on a joining process, belonging to the friction stir forming (FSF) techniques, which was first introduced in 2002 by Nishihara [12] as a useful method for deforming materials, especially metals. Indeed, this technique, by using the same process sequence of friction stir welding, exploits heat and internal forces allowing a consistent deformation of the material to perform connection by mechanical interlocking. Ahuja et al. [13], for example, employed this process to produce Cu-W composite by introducing W-inserts in the cavity of a Cu-block and, subsequently, processing the compound with a flat tool to obtain a proper intermixing of copper and tungsten. The process consists of fixing a formed plate on a matrix with negative shapes of the parts that have to be manufactured on. A rotating rigid tool is plunged inside the plate and, subsequently, moves along its surface deforming and pushing the material to fill the cavity of the matrix bearing area. As a result, the die shape is transferred on the surface of the formed plate. The fundamental variables of the process are the shape of the tool, the rotation rate, the linear feed velocity, the immersion depth, the rigid tool shape and the inclination angle between the tool axis and the plate plane. As previously mentioned, the pins obtained by FSF can be used as mechanical fasteners for joining parts without adding material for the connection. The joining phase can take place in a single step or in two steps.

Ohashi et al. [14] applied this process to generate cylindrical extruded pins on aluminum alloy sheets. The pins can be inserted, subsequently, in a pre-holed part where they are squashed creating the mechanical interlocking in a typical two-steps sequence. Conte et al. [15] presented the one-step process variant, which consists in shaping the pins by means of FSF process and in exploiting the movement of the rigid tool to push the material through the bearing area of a pre-holed sheet to be assembled and squeezing the extruded pin on a rigid wall placed below the working zone making a locking head.

In the work, herein presented, the feasibility of the one-step FSF process was investigated for connecting dissimilar materials. Specifically, materials with consistent different melting temperatures, a metallic-base alloy and a plastic-base material, have been processed. According to that, it has to be highlighted that the criticism related to this combination is that the heat generated by friction has to be properly balanced. Indeed, on one side, the temperature has to be adequate to soften the metallic part, allowing its proper stirring and deformation but, on the other side, it has to be limited to avoid that the plastic part loses its strength, important to guarantee the right extrusion conditions or, in the most critic process circumstances, that the polymeric resin deteriorate, thermally. According to that and considering some process parameters analyzed in previous studies, different process configurations (with and without additional laminas between the sheets to be connected) were investigated, analyzed and the results justified, properly.

2. Equipment, Materials and Methods

2.1. The customized equipment

The FSF technique was introduced as joining variant for hybrid connection in 2017 by Ohashi et al. [16].
Conte et al. [17] and Gagliardi et al. [18] attempted to use the FSF as a joining technique. Two main steps can be defined: first, pins are produced by extruding the metal sheet through holes drilled on a forming die (Fig. 1 (a)) and subsequently, the extruded rivets are used to connect the metal sheet with another pre-holed part (composed of metal or composite as well) creating a joint (Fig. 1 (b)).

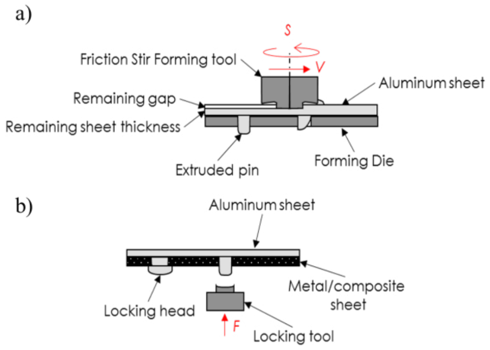

Fig. 1. FSF technique in two steps: (a) pin extrusion; (b) joining step [18].

As introduced, the aim of this work was to perform the joining in a single step, thus combining the pin extrution phase with the joining itself. To do that, a customised equipment was designed and placed on a general purpose milling machine. Fig. 2 shows the parts the equipment is composed of. It consists of: (i) a steel container, where the forming die is positioned inside; (ii) a forming die, wich section and height are lower than the container in order to keep and lock the element to joint inside; (iii) a steel clamping frame, employed to lock the sheet during the forming process; (iv) a rigid punch, named FSF tool, with a shoulder of 15mm and a probe of 5mm.

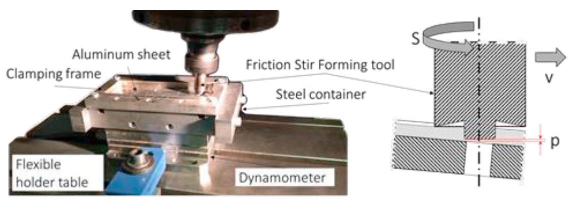

Fig.2. The designed FSF equipment [18]

All these parts were positioned on a dynamoter, used to monitor the forming forces, and than placed on a flexible holder table that allows to impose a tilte angle higher than zero degree.

The forming die is characterised by a double line of holes having a diameter equal to 4mm and a distance from each other of 20mm. The holes allow to flow down the joining elements and to constrine the maximum height contemporary. The punch geometry was performed according to Ohashi et al. [2].

2.2. The joined materials

The first material selected for performing the research activities is the aluminum EN AW-1050A-H111. Samples of 180x80x3mm were cut from a sheet.

The second material, chosen as joining element and placed below the aluminum, is the poly-ether-eter-ketone (PEEK). It is an organic polymer belonging to the family of poly-aryl-ether-ketones (Paeks), high temperature thermoplastic polymers, consisting of an aromatic molecular chain with a "zigzag" conformation. PEEK is a semicrystalline polymer, consisting of an amorphous phase and a crystalline phase, varying between 30 and 35%. Its particular structure gives the polymer high strength and stability from both a mechanical and chemical point of view. For these reasons the quality of its use is widely recognized also in critical automotive and transportation applications (such as for the transmission wheels). PEEK samples, equal actually to the forming die section and drilled according to the position of holes on this latter, were cut from a sheet for a final dimension of 170x55x3mm.

The materials' properties are reported in Table 1.

Table 1. Mechanical and thermal properties of the investigated materials.

	EN AW-1050A-H111	PEEK
Young's Modulus (GPa)	69	4
Tensile Strength (MPa)	65-90	97
Elongation (%)	30	43
Thermal Conductivity (W/mK)	230	0.3
Spec. Heat Capacity (J/Kg K)	900	1700

2.3. The applied methods

At the process starting point, the FSF tool is plugged into the metal sheet up to a controlled residual depth (p), measured as shown in Fig. 2 and equal to 0.05mm. The combination of rotational (S) and linear movement (v) of this tool in parallel to the sheet plane allows the pins to be extruded through the holes of the forming die and to join the dissimilar materials.

As introduced previously, in this experimental investigation a double approach was tested, including or not an additional layer between the two materials. More in particular, at the beginning the process was performed to manufacture a "naked" joint, made of aluminum and PEEK. After that, the same process was repeated by positioning a thin layer of AISI 304 steel or glass fiber composite between the two joining elements. For both the adopted layers, the geometry is fixed equal to 170x55x0.6mm. The scope of these process variants will be better explained in the discussion of the results.

Taking into account the knowledge gained from a previous study carried out from some of the authors [15], a new combination of parameters was tested for the above mentioned test configurations. More in detail, the rotational speed and the forming velocity v were set respectively to 3000rpm and 600mm/min. The idle time (time between the punch positioning at p distance from the lower sheet and the linear movement start) was fixed equal to zero, while the tilt angle to 5°.

3. Discussion of results

The first experimental tests were performed aiming at creating a solid joint using just the two plates to be connected, i.e., the superimposed AA-1050 and the underlying thermoplastic peek parts. This solution did not result in a worthy connection with a weak interaction obtained at the end of the test with the two plates that resulted almost unconnected. Furthermore, looking at the sample from the bottom side (Fig. 3), just the first metallic pins of the manufactured row are visible inside the plastic, while once the process reaches the operating conditions just the melted PEEK seems to fill the pre-holed bearing zones.

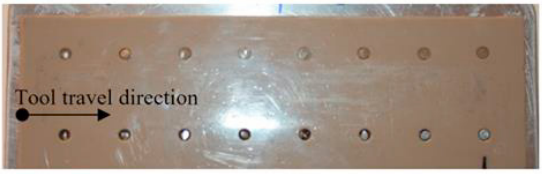

Fig. 3. Bottom side of the connection between AA-1050 and PEEK.

To clearly understand what happened during the forming phase, the specimen was cut along the centerline of the holes (Fig. 4).

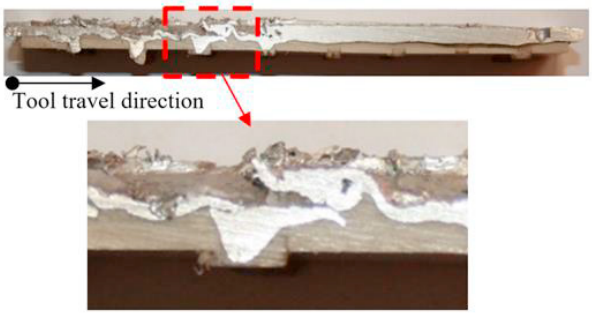

Fig. 4. Section along the pin centerline of the pins (AA-1050 and PEEK).

Two process weaknesses can be observed. Specifically, being the PEEK a thermoplastic material, it is characterized by a glass transition temperature around which the material loses its rigidity, abruptly. Considering that, at the beginning of the process, when the generated heat by friction is still not relevant, the plastic plate is able to withstand to the tool movement generating the process forces, which allow the pins to be shaped. Anyway, in this first process phase, the upper side of the PEEK surface melts, without affecting the below layer of the plate owing to the low material conductivity. This melted part results to be mixed with the stirred aluminum resulting in wide material ruptures. Subsequently, the generated heat affects the whole thickness of the polymeric plate, which loses its rigidity and does not allow the extrusion phase, anymore.

Considering this first experimental evidence, the next step of the performed activity was moved following an inspiration coming from literature [19]. Specifically, a thin steel plate was interlaid between AA1050 and PEEK to avoid the direct contact between the surfaces of metal and polymer, hindering the mixing of the two materials. The lower side of the PEEK plate and the cross section of the joined parts are reported in Fig. 5.

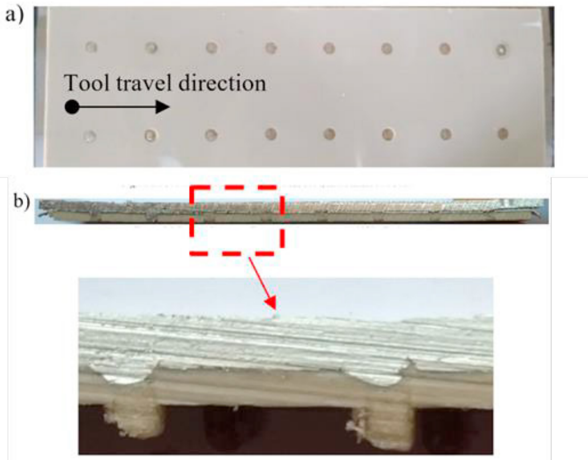

Fig. 5. a) bottom side and b) cross section of the connection between AA-1050, steel and PEEK.

The main evidence resulting from the second process configuration is that the interaction between AA-1050 and PEEK was avoided and this led to an upper side of the aluminum sheet without rupture solving one of the process defects arisen in the previous configuration. Nevertheless, the steel plate, being characterized by an elevated conductivity did not hinder the heating flow to the plastic plate, which, therefore, lost its rigidity owing to its temperature increment and no pin extrusion was permitted.

Synthetizing, the interlayer plate was fundamental to avoid the materials interaction, but, to be wholly performant to the process feasibility, a new material was chosen, characterized by low conductivity.

The selected material was a glass fiber reinforced polymeric composite. Both the glass fibers and the polymeric matrix boast isolating properties, which can block the generated heat during FSF to the metallic side preserving the deterioration of the PEEK properties related to the temperature variation. Furthermore, the chosen solution was further supported because of its lightweighting and toughness properties owing to, respectively, its elevated strength/density ratio and ductility of the polymeric matrix, which preserves the integrity of the glass fiber reinforcements.

The process feasibility was, therefore, proven by using this last configuration. According to that, both the glass reinforced plastic and the PEEK plates were pre-holed to generate the bearing zone fundamental for the pin extrusion. Considering the preliminary results arisen from this process setting, it was observedthat if the same hole diameter is performed both on the PEEK and on the glass-reinforced plate, owing to the process dynamics, the actual pin size is reduced since the glass woven is pushed to the bearing area (Fig. 6). According to that, the holes on the isolating layer were enlarged, achieving a diameter 1mm wider than the nominal one.

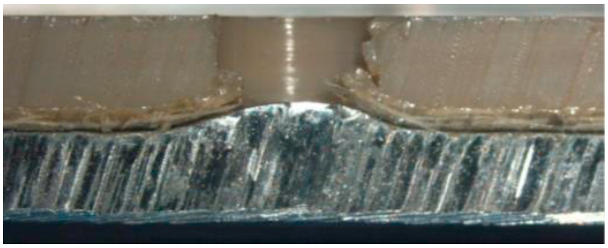

Fig. 6. Bearing area if PEEK and glass-reinforced plates have the same diameter of the die holes.

Performing the test using the best geometrical configuration and setting the same process variables assessed for the previous cases, the joined parts shown in Fig. 7 have been obtained.

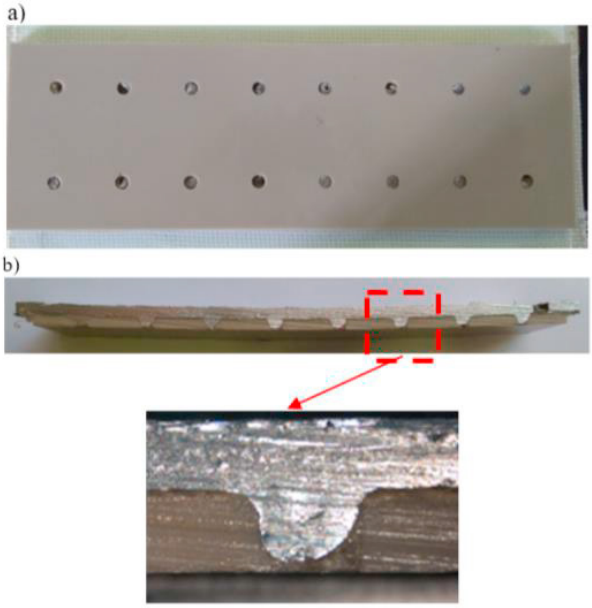

Fig. 7. a) bottom side and b) cross section of the connection between AA-1050, glass fiber composite and PEEK.

It is worth to observing that the metallic bulges of the extruded pins almost reached the bottom side of the PEEK plate.

4. Conclusions

In this study a preliminary experimental investigation was performed in order to test the FSF feasibility as joining technique in a single process step. Indeed, the state of the art has proposed FSF as a valuable joining solution to connect also dissimilar parts, but dividing the process in two subsequent steps. That solution requires longer execution time, thus reducing the process competitiveness. On the contrary, extruding and joining the pins in one step results in a more promising process for the real industrial application. For this purpose, a customized equipment was designed and employed during the experimental investigation. The evidences highlighted that the joining between dissimilar materials is firstly influenced by the thermal properties of the materials to be connected. The lower melting point of the polymeric material makes it soft owing to the heat generated by the friction between punch and joined parts, thus reducing its stiffness and capacity to allow the pin extrusion. Therefore, the heat transmission needs to be reduced to preserve the rigidity of the system. To pursue this aim, three distinct configurations were tested discovering that the introduction of a thin glass fiber layer between the aluminum alloy and the PEEK is a valuable solution since it allows the extrusion of the metal and therefore the forming of the joint. This solution needs to be further investigated for improving the process outcome.

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